table) the ASME code permits an increase in the allowable stress of 1.2 making it the upset allowable stress 70.3 MPa (10,200 psi). The actual stress still exceeds this increased allowable stress by over a factor of two. Based on this analysis alone the design of the flywheel is inadequate and not suited for its intended use.

This alone should indicate that the housing should be redesigned. However, the results of the analysis will be scaled and checked for the typical operating conditions given in Table 2 under the "Fatigue Calcs" column with a vertical G-load of 1±2.5. This corresponds to a vertical G-load of 3.5 compared to the value of 4 used in the Caterpillar FEA analysis. Applying this load to the lighter transmission results in a maximum of 97.2 MPa (14,100 psi). Since this high stress is localized, the ASME code allows for an increase in the allowable stress by a factor of 1.5. This the allowable stress for a high localized normal operating stress is 87.93 MPa (12,750) for this aluminum. The actual stress still exceeds the increased allowable stress. This confirms that under normal operating conditions the stress in the housing exceeds the allowable stress. This shows that the housing does not meet the requirements for occasional upset loads nor does it meet the requirements for the normal operating loads indicating that it is not adequate for its intended use.

One final check of the results is to compare the actual stress with any other published information on the fatigue behavior of A356.0 T6 aluminum. In the ASM Handbook Volume 19 "Fatigue and Fracture" R. Bucci presents a table of typical mechanical properties of premium-grade aluminum castings. The table provides a fatigue strength of A356.0 T6 aluminum of 90 MPa (13,050 psi). Recall that for fatigue cracking not to occur the cyclic stress should be considerably below the fatigue strength. In this case the actual cyclic stress of 97.2 MPa (14,100 psi), calculated using the actual C10/12 flywheel housing weight and a G load of 3.5, exceeds the published fatigue strength. Thus, it would be expected that fatigue cracking in the flywheel housing could occur with this design under these loading conditions.

In addition to a problem with cracking at the bolt holes, a problem of loosening of the bolts that attach the housing to the engine block has been documented. The analyses provided by Caterpillar investigating the stresses in a C10/12 flywheel housing also evaluated the bolted joint connecting the housing to the engine block. Again, this analysis was based on M14 bolts attaching the housing to the block instead of the actual M12 size bolts. However, the results can be used to determine the adequacy of the actual joint using the M12 bolts.

The bolt joint analysis (BJA) provided is the only information provided by Caterpillar that indicates any analysis was performed on this bolted connection and nothing was provided concurrent with the design of the C10/12 flywheel housing. As with the FEA, no background information or documentation was provided, no criteria as to what constitutes an adequate bolt joint diagram or any other acceptance criteria regarding the connection is provided. Thus, accepted engineering practice and experience was used to interpret the results.

EXHIBIT
tabbies
Exhibit G
Part 2 of 2

In the design of a bolted joint (in this case the flywheel housing bolted to the engine block) it is paramount to prevent loosening of the connection under fatigue (vibration) conditions. Further, the flywheel is in an inherent fatigue condition so this is a critical issue. The most important factor in preventing vibration loosening is to maintain the initial preload on the bolt as introduced during installation by applying the proper bolt torque. The best way to minimize the influence of vibration loosening is to have a high joint stiffness relative to the bolt stiffness. In the analysis provided, a joint stiffness of 588,210 N/mm (3.36×10^6 lb/in,) is presented. Since this is only a function of the flange (housing) geometry it will not be affected by different size bolts and will be used in further analysis. The stiffness of the M14 bolt is given as 788,291 N/mm (4.5×10^6 lb/in.). Thus, the ratio of the joint stiffness to the bolt stiffness, R, is 0.746. The "Fastener Design Manual" NASA Reference Publication 1228 printed in 1990 states in the section of Fatigue (Cyclic) Loading of Bolts:

> *In a normal clamped joint Kc* [the joint stiffness] *is much larger than K_b* [the bolt stiffness] *($R \approx 5.0$ for steel bolt and flanges), so that the bolt load does not increase much as the external load F_e* [vibration load] *is applied.*

It goes on to state:

> *Note that the flatter the slope of OA (or the larger ratio OC/OB becomes),* [meaning a higher ratio R] *the smaller the effect F_e has on the bolt. Therefore, using more smaller-diameter fasteners rather than a few large-diameter fasteners will give a more fatigue-resistant joint.*

In Shigley's "Standard Handbook of Machine Design" in a section on reducing fatigue problems in bolted and riveted joints he states:

> *It helps to increase the ratio between the stiffness of the joint and the stiffness of the bolt so that the joint will absorb a larger percentage of the applied load excursions.*

Finally, the EPRI 'Good Bolting Practices" manual on small bolts and threaded fasteners states in a section on vibration loosening states:

> *... use longer bolts – the longer the better. (A bolt having a length to diameter ratio of 8:1 or more will "never" loosen, some experts say.)*

This is another way of stating that the joint-bolt stiffness ratio, R, should be as high as possible. All of these references indicate that a high joint to bolt stiffness ratio is needed to prevent loosening under fatigue conditions. The calculated joint-bolt stiffness presented for the M14 bolt is only 0.746, considerably less that the 5 recommended by NASA. Thus, given these results, it is concluded that the "unacceptable shape" of the joint diagram stated in the Caterpillar analysis is that stiffness ratio is insufficient to prevent vibration loosening.

The results of the Caterpillar analysis provided concluded that the bolt joint diagram has an unacceptable shape. However, the results are based on M14 bolts that are larger in diameter than the actual M12 bolts used in the actual housings. Thus, using smaller diameter M12 bolts will increase the joint ratio. This increase can be simply scaled based on the relative difference in cross-sectional areas of the M12 and M14 bolts. An M12 bolt has a cross-sectional area that is 0.733 times that of a M14 bolt. Given this decrease in bolt stiffness, with the same joint stiffness, the joint-bolt stiffness ratio will increase by the reciprocal amount, i.e. the stiffness ratio, R, for an M12 bolt will be 1.364 times that of the M14 bolt. Thus, the stiffness ratio, R, for the M12 bolted joint assembly is 1.02 compared to 0.746 for the M14 bolt. This value is still significantly less than what is desired for a well designed bolted connection. Thus, the bolted joint connecting the flywheel housing to the engine block using the M12 bolts is inadequate for vibration conditions and there is a likelihood that the bolts could loosen.

In addition to the problems with the bolted joint stiffness, there are other concerns with the design that have not been addressed at all by Caterpillar in their analysis. First and most important is that the Caterpillar analysis only considered the loads resulting from the G-loading on the transmission. These loads act to pull apart (and compress) the flywheel housing engine block joint. In addition to these loads there are torque loads put on the connection resulting from the engine torque. These loads tend to slide the connection between the housing and engine against each other at a direction perpendicular to the bolts. If the bolts loosen then the housing will slide relative to the block and result in the housing impacting the bolts. This will result in the bolt threads contacting the inside surfaces of the housing bolt holes. This is the exact type of damage observed in one of the flywheel housings examined. In addition, the torque from the engines has increased by 57% over the years meaning that this has become more of a design problem as the torque increased.

The EPRI handbook states in a section of vibration loosening:

> *The vibratory force must have a component at right angles to the axis of the bolt - a force which, when high enough, will cause the joint members to slip past each other. (Vibratory forces parallel to the bolt axis will loosen the bolt - causing it to lose perhaps 10-20% of initial preload - but only transverse forces will fully loosen it.*

In the case of the flywheel housings the G-force loads are the parallel forces and the torque forces are the transverse forces. These added torque loads on the connection tend to make the inadequate joint worse. They were completely omitted from the Caterpillar analysis.

The NASA fastener design manual also has a section on combined loading. They provide criteria that can be applied to a bolted joint when it is subjected to both tension (G loads on the transmission) and shear (transverse loading resulting from the engine torque). This was not done in the Caterpillar analysis.

The last effect that has not been addressed by the Caterpillar analysis is the effect of temperature excursions on the bolted connection. This becomes an issue when there are different materials in the bolted connection that have different coefficients of thermal expansion. In this case, for a given temperature increase, the aluminum will expand about 1.6 times as much as the steel bolt. What this means is that the load on the bolt will increase, further increasing the likelihood of loosening, particularly when combined with the vibration effects and the combined loading effects. In this regard, a patent assigned to Caterpillar describes a new flywheel housing design that has a seal that is intended to overcome problems in aluminum flywheel housings associated with thermal expansion, relative movement between the housing and engine block, cracking or destroyed engine bolts. The Trans-Spec C10/12 flywheel housings do not incorporate this patented design feature.

The laboratory inspection of the flywheel housings also showed areas of anomalous wear patterns located below the circular openings and corresponding to the location of the oil pan on the bottom of the engine block. These wear patterns are visible in Figure 1 and in Figure 14. This wear is the result of contact and relative movement between the housing and the oil pan. These components should not be in contact during operation. Further, any contact between the components could transfer additional load to the bolted joint from the vibration experienced during normal operation adding addition loads to an inherently under-designed housing and connection. The fact that there is wear indicates that there was contact between the two components.

4.0 SUMMARY

The laboratory investigation revealed failures in aluminum C10/12 flywheel housings resulting from cracking and loosening bolts. The cracking of the housings was the result of fatigue in the area of the bolt holes. Further, anomalous wear was identified on the flywheel housing indicating contact and relative movement from the housing and engine oil pan. An engineering analysis of the flywheel housing and the bolted connection between the housing and the engine block revealed inherent design defects. It is my opinion that these design defects are: overstressing of the flywheel housings under normal operating conditions causing cracks to initiate and propagate; and an under-designed bolted connection resulting from improper joint design and unaccounted for torsional and thermal loads causing the bolts to loosen. These defects could be remedied by proper engineering design and analysis.

5.0 REFERENCES

The following is a list of information relied on in the course of the investigation:

- Three flywheel housings and components provided by Trans-Spec
- Visits to Trans-Spec facilities to inspect trucks and equipment
- The following deposition transcripts:
    1. Robert Barton
    2. Richard Bowes
    3. Harold Calderbank
    4. Al Cardozo
    5. Clarissa Colmer
    6. Troy Guidotti
    7. Kevin Holmes
    8. Able LaFlash
    9. Ralph Lind
    10. Donald Medbery
    11. Stephen Schoening
    12. 3-Jay Howard (with exhibits)
    13. Richard Bowes (with exhibits)
- ASM Handbook Volume 19: *Fatigue and Fracture* 1996
- ASM Handbook Volume 11: *Failure Analysis and Prevention* 2002
- ASM Handbook Volume 9: Fractography and *Atlas of Fractographs 8^{th} Ed* 1974
- *Atlas of Fatigue Curves* by Howard Boyer, American Society of Metals 1986
- *Standard Handbook of Machine Design* by Shigley and Mischke, McGraw-Hill 1986
- *Good Bolting Practices: A reference manual for nuclear power plant maintenance personnel Volume 2: large bolt manual.* Electric Power research Institute (EPRI) Dec 1990.
- *Good Bolting Practices: A reference manual for nuclear power plant maintenance personnel Volume 1: Small bolts and threaded fasteners.* Electric Power research Institute (EPRI) Dec 1987.
- *Fastener Design Manual,* NASA Reference Publication 1228 1990
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- Laboratory testing and analysis results
- Web site material from Cateripllar
- Web site material from Meritor
- Web site material from Eaton-Fuller
- Web material obtained on Caterpillar 3176, C10 and C12 engines
- Photographs taken of flywheel housings located at Caterpillar
- All documents provided by Caterpillar (Bates numbers 1-4014); Caterpillars responses to interrogatories and the attached exhibits
- All documents provided by Trans-Spec to Caterpillar except those stored on-site at Trans-Spec.

- Final invoice produce by Minuteman Trucks, Inc.
- My extensive engineering experience and expertise

6.0 PAST TESTIMONY AND DEPOSITIONS FOR THOMAS H. SERVICE, PHD, PE

- John DiPaolo, Jr., et als. v. New England Welding Supply, Deposition for Plaintiff in Boston MA 12/2/2005
- Inter Export Trading Corp. v. Warren Svendsen, Testimony for Plaintiff in Superior Court Orange County CA, Case No. 00CC09131, 7/11/2001
- Jimmy Rodgers v. Metabo Corp., Deposition for Defense in Northern District of Mississippi Greenville Div, No. 4:00CV147-D-B, 1/26/2001
- Lieselotte Suskind et al. v. Home Depot, Deposition for Defense in Boston MA 10/5/2000
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- Georgia-Pacific et al. v. F & W Construction, et al. Deposition for Plaintiff in Montgomery AL, 7/12/1999
- Forney Industries, Deposition for Defense in Columbia SC, 9/1998
- Taorima v. Black & Decker, Deposition for Defense in New York NY, 9/1995

7.0 CURRENT CV WITH PUBLICATIONS FOR THOMAS H SERVICE, PHD,PE

Thomas H. Service, Ph.D., P.E.

EDUCATION: Ph.D., Mechanical Engineering, University of Massachusetts
M.S.M.E., University of Massachusetts
B.S.M.E., University of Massachusetts, with honors

PROFESSIONAL REGISTRATIONS: Registered Professional Mechanical Engineer, Massachusetts No. 32791, New York No. 081773

PROFESSIONAL SOCIETIES: Member of American Society of Mechanical Engineers, 25 years
Past Member of ASME Reliability, Stress Analysis and Failure Prevention Committee - Past Associate Editor, Journal of Mechanical Design
Member ANSI B7.1 Committee

PROFESSIONAL EXPERIENCE: Dr. Service is a Principal Engineer with Altran Corporation. He has over 25 years experience in the area of mechanical engineering, failure analysis and accident investigation of structures, machinery and mechanical components. He has provided engineering consulting services to many Fortune 100 manufacturing companies, nuclear and fossil utilities, the pulp and paper industry, the insurance industry, State and local municipalities as well as providing expert testimony for litigation.

He has specific expertise in structural analysis with extensive experience in structural reliability and condition assessment. He has a strong background in materials engineering and mechanical behavior of materials, machine design, elasticity, plasticity, fatigue, fracture, stress corrosion, creep, deterministic and probabilistic fracture mechanics. Structural reliability, design analysis and behavior of materials, brittle ceramics and bonded-abrasives are topics that Dr. Service has published and spoken about.

Dr. Service is responsible for mechanical, structural, materials and analytical engineering evaluations and failure analysis investigations. Specific analyses and investigations have included ASME Code pressure vessels and piping systems, Yankee dryers, pulp and paper equipment, pump bodies, fluid couplers, railcars and equipment, glass melters, rotary kilns, ball mills, conveyors, rock bins, valves, fans, retaining walls, presses, extruders, bolts and shafts, rolls, components for space qualification, power tools, glass and ceramic components, grinding wheels and more. He has extensive knowledge of ASME piping and pressure

vessel codes as well as other industrial related fabrication and safety standards.

Prior to joining Altran Corporation, Dr. Service held the position of Senior Engineer at Thielsch Engineering. He was responsible for analyses and investigations involving structural failure and fracture of a wide variety of industrial machinery and equipment. His clients ranged from large companies and government agencies such as the Army, Department of Energy, New York City Jet Propulsion Laboratory, 3-M, General Motors, Georgia Pacific, United Technologies, Factory Mutual, HSB/IRI, Black & Decker, Norton and Cincinnati Milacron as well as small local industry with limited technical resources.

GRANTS AND AWARDS:

"Suspension Bridge Cable Degradation," with R. Latanision from NYC TBTA, 2000 ($1,850,000).

"Vibration in Portable Grinding Wheels," from Grinding Wheel Institute 1995 ($93,000).

"Proof Testing High Speed Cutoff Wheels," Grinding Wheel Manufacturers Consortium 1993 ($30,000).

"Creep and Aging of Resinoid-Bonded Abrasives," from the Grinding Wheel Institute. 1990-1991 ($50,200).

"Grinding Wheel Laboratory," with J. E. Ritter from the Grinding Wheel Institute. 1986-1989 ($100,000/ year).

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National Academy of Science East European Scientific Exchange Program. Visit to the German Democratic Republic for one month in 1988.

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"Maximum Likelihood Estimation Techniques for Concurrent Flaw Subpopulations," (with D. Sonderman, J. Ritter and S. Yuhaski), J. Mat. Sci., **20** 207-12 (1985).

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8.0 COMPENSATION RATES

ALTRAN CONFIDENTIAL

ALTRAN CORPORATION
Rates, Terms, and Conditions

Classification	Hourly Rate
Senior Consultant 1 (Variable Rate)	$330.00-$400.00
Senior Consultant 2	275.00
Senior Consultant 3	230.00
Senior Scientist/Engineer	180.00
Engineering Support	125.00
Technician	80.00
Administrative Support	60.00

The above rates are inclusive of salary, overhead expenses, fees, benefits, vacation allowance, sick leave, holiday pay, taxes, and insurance. These rates include travel time not to exceed ten hours per day. Overtime rates for after hours and weekend work will be billed at the straight time rate with a 25% premium. These rates will remain in effect through December 31, 2003. Court testimony and deposition time for any classification will be charged at a premium of 30% above the rates listed above.

All direct charges such as travel, subsistence, telephone, materials, equipment, outside services, etc., will be billed at cost plus a 15% administration fee. Personal automobile mileage will be billed at $0.36 per mile.

General laboratory usage and mechanical testing will be billed at $100/hour. This rate will include normal laboratory consumables such as mounting material, machining tools, polishing materials, and chemicals. Specialized supplies such as test fixtures, unusual measurement equipment, unusual sectioning tools, off site storage fees and disposal fees will be billed at cost plus 15%. Analytical services, such as scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), wavelength dispersive spectroscopy (WDS), infrared spectrometry (FTIR), gas chromatography (GS), X-ray diffraction (XRD), mass spectrometry (MS), and differential scanning calorimetry (DSC) will be billed at $225/hr. A fee of $150/hour will be billed for database literature research. Videoconferencing services will be billed at $150/hour.

Unless otherwise provided through advance written agreement, Altran Corporation does not provide services on a contingency basis nor will delays due to third party billing or settlements be considered acceptable. The terms for payment are net 30 days from the date of invoice. Invoicing will be monthly. This agreement is drawn between the primary client and Altran Corporation and is exclusive of any arrangements made between the Altran Corporation, the client firm, and its client. Unless other arrangements are made under written agreement, an estimate will be provided for the effort to be undertaken. An up-front retainer of 15% of the estimated cost of the support effort will be required before any work is undertaken, unless other arrangements are made in advance.

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Storage of bulky physical evidence will be charged at $150 per month, beginning at such time as the evidence is no longer directly required for analysis or examination. Final disposition of any physical evidence will be decided by the client firm and suitable arrangements must be made for long-term storage, return shipping, or disposal; whichever is desired.

The above terms are considered in force until such time as the litigation matter for which support is being contracted is adjudicated. Failure to make payment according to this agreement will result in the following actions:

- a monthly interest rate will be assessed in the amount of 1.5% of the outstanding balance, beginning 60 days after date of invoice
- all activities by Altran Corporation will be stopped following 60 days of non-payment of the amount due
- failure to make timely payments will be considered for legal action and the cost of such action will be charged to the client firm

The above terms have been reviewed and accepted on this day, the 26th day of July, 2005, by Nancy H. Reimer, representing the firm of Trans-Spec Truck Service, Inc., in the matter of Trans-Spec v. Caterpillar Inc.

For Altran Corporation:

Thomas H Service, PhD, PE
printed name

signature

For the Client:

NANCY H REIMER
printed name

signature

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Very truly yours,

ALTRAN CORPORATION

Thomas H. Service, PhD, PE
Principal Engineer